An update on a two-habit ice cloud model and a two-layer surface snow model for optical property simulations

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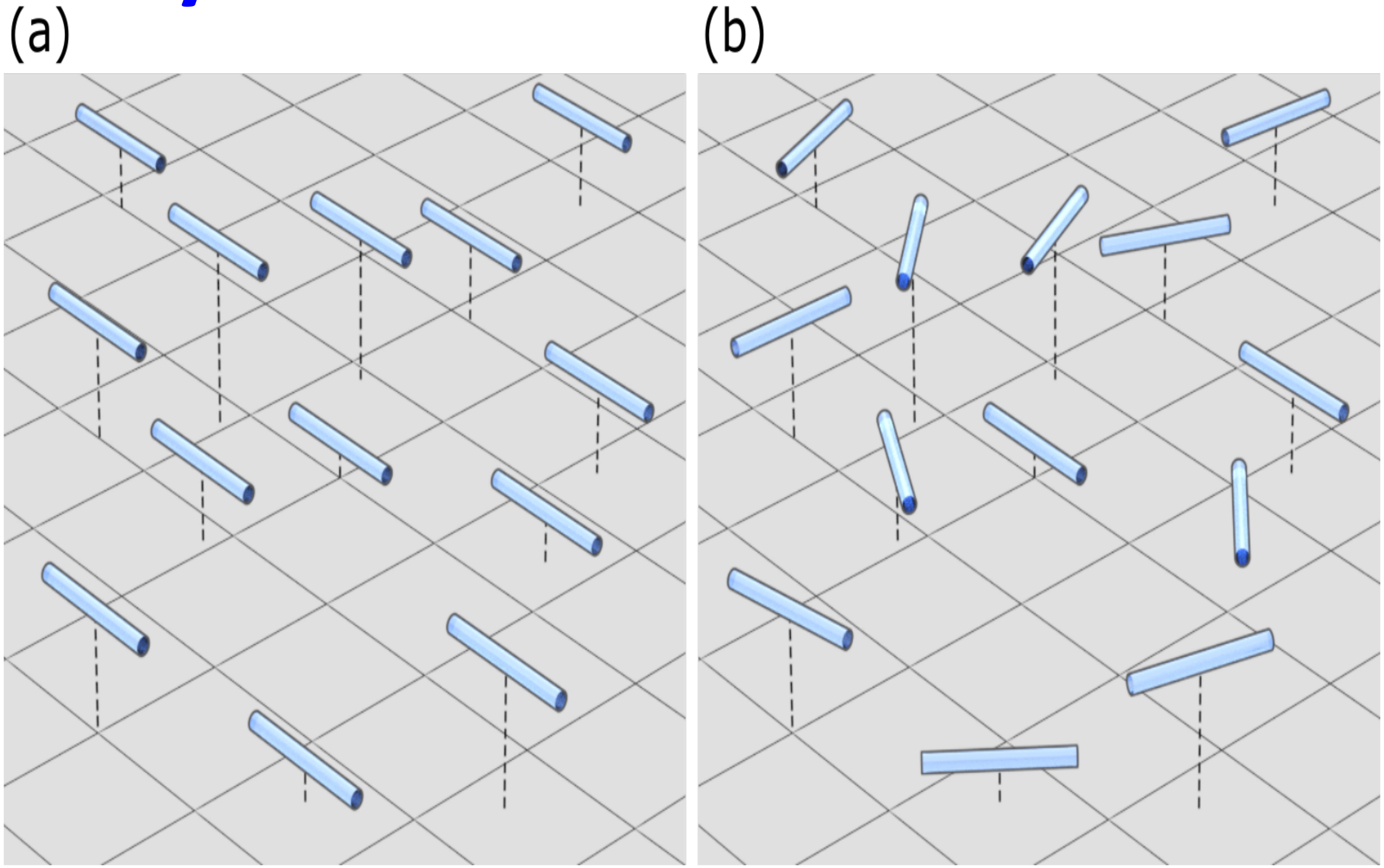
Part I: Ice cloud model

Early Wisdom



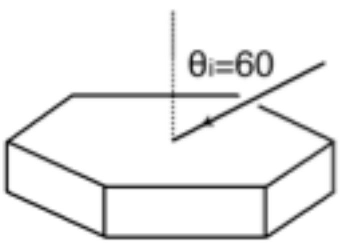
Two horizontally oriented cylinder models (Liou, 1972): (a) specific orientation in the horizontal plane and (b) random orientations in the horizontal plane.

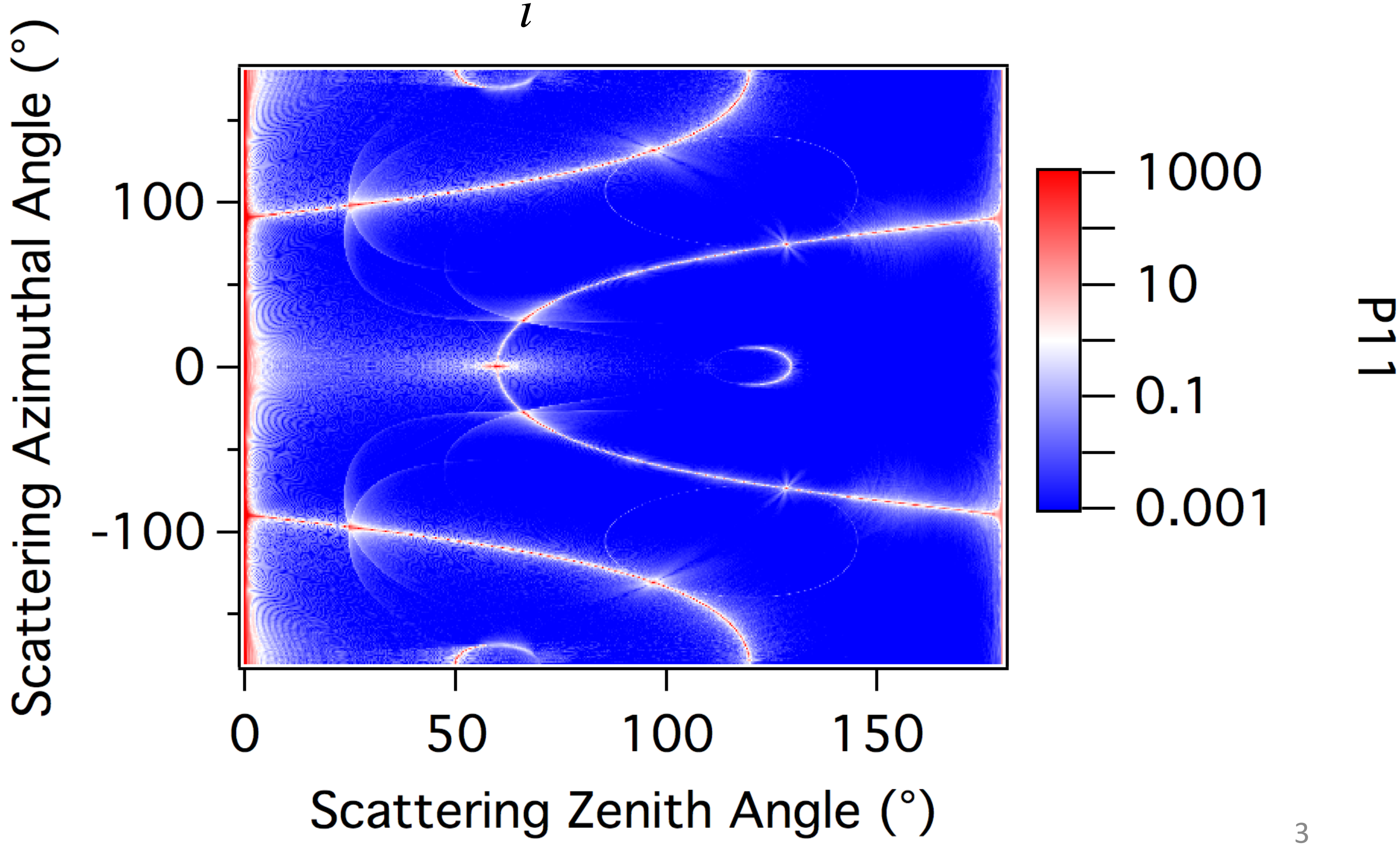
The single-scattering properties of specific oriented ice crystals are very complicated (e.g., the phase function is two-dimensional)

$$2\pi a / \lambda = 1000$$

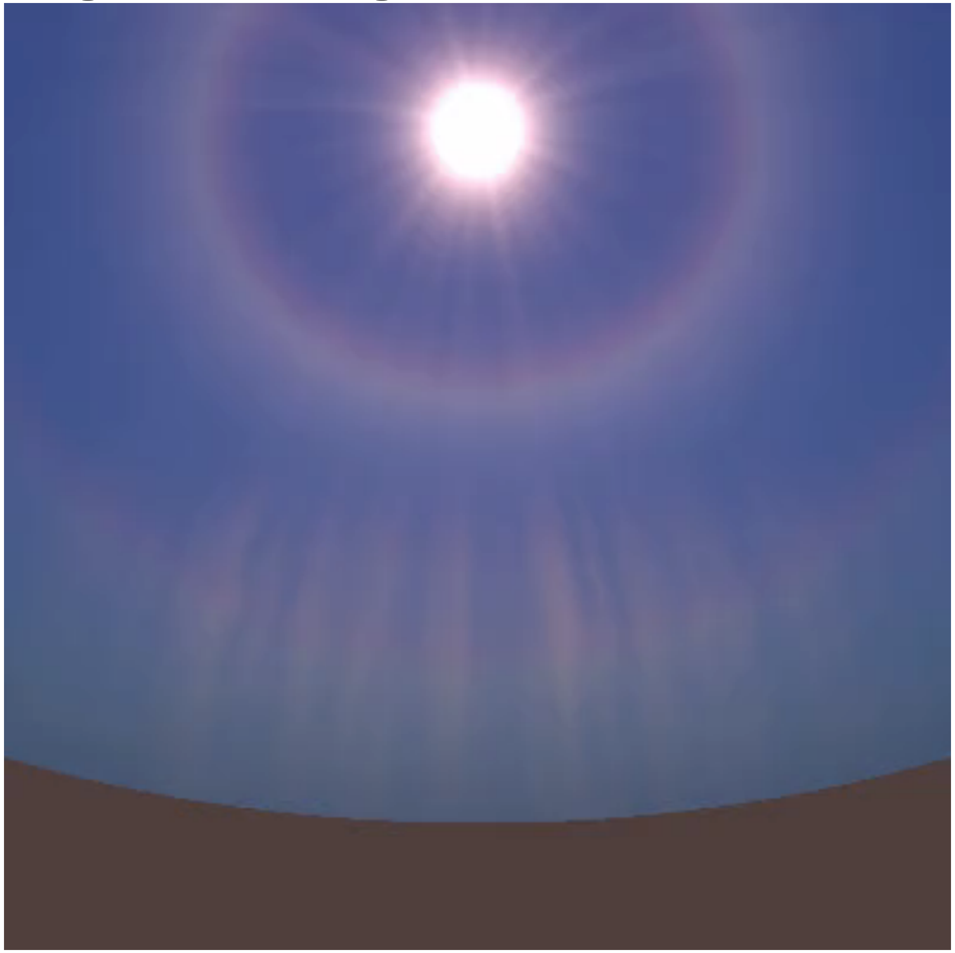
$$a / L = 8, \ \lambda = 0.532 \mu m$$

$$\theta_i = 60^o$$





Optical phenomena by oriented plates

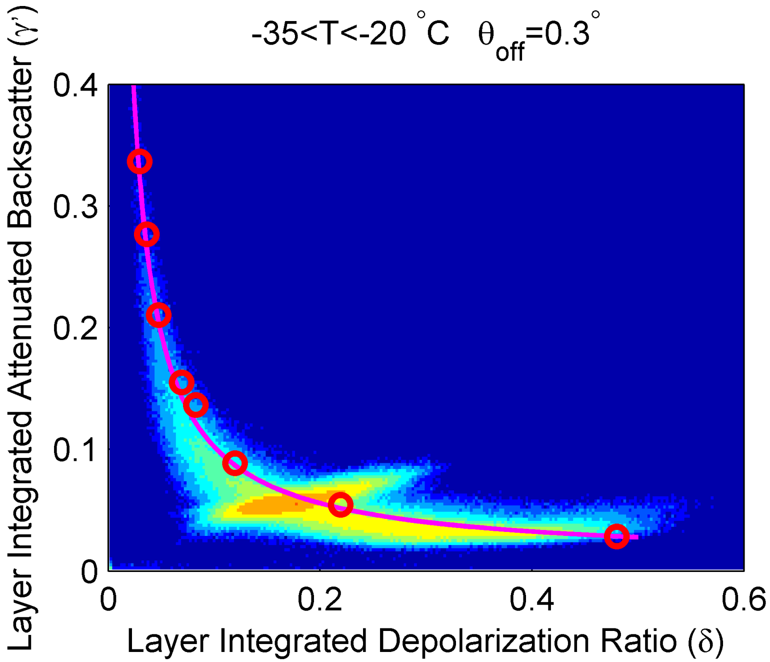


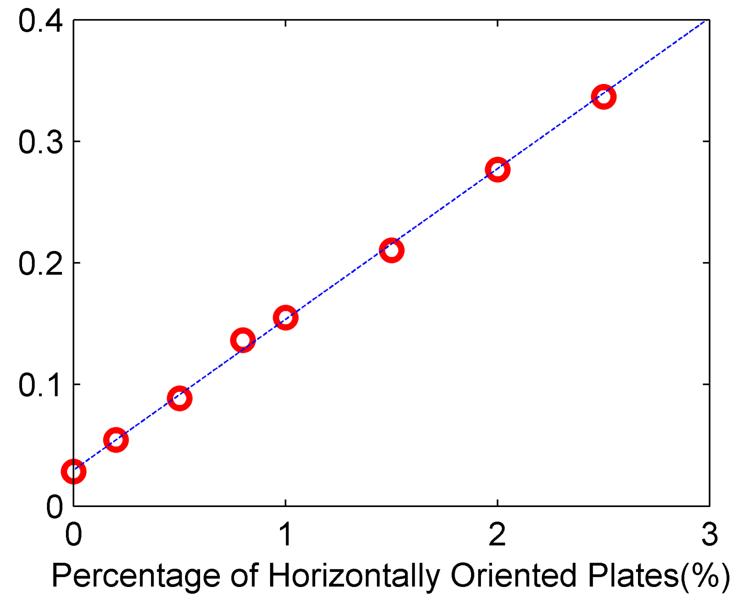
- False color sky simulations
  - Red: $I_{1.064}$ x 3
  - Green: $I_{0.532}$ x 0.7
  - Blue: $I_{0.355}$ x 2
- Single-scattering RTM
- PPH cloud layer assumption
- Fish-eye camera

- COT: 0.3
- CER: 100 µm
- HOP fraction: 7.9%
- HOP tilting angle: 1.0˚

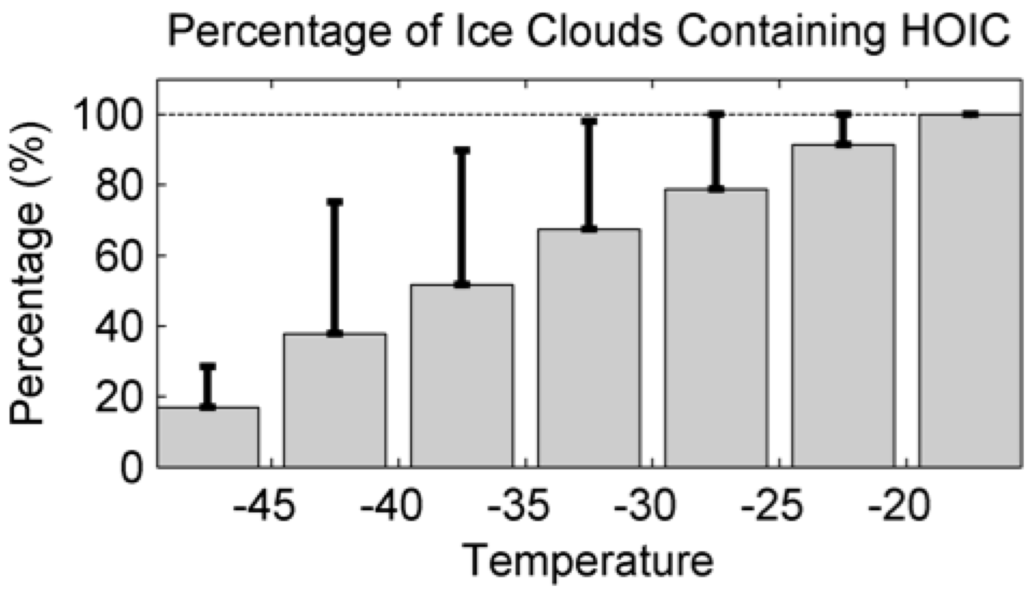
Sun-dogs and sun-pillar appear in the simulated sky

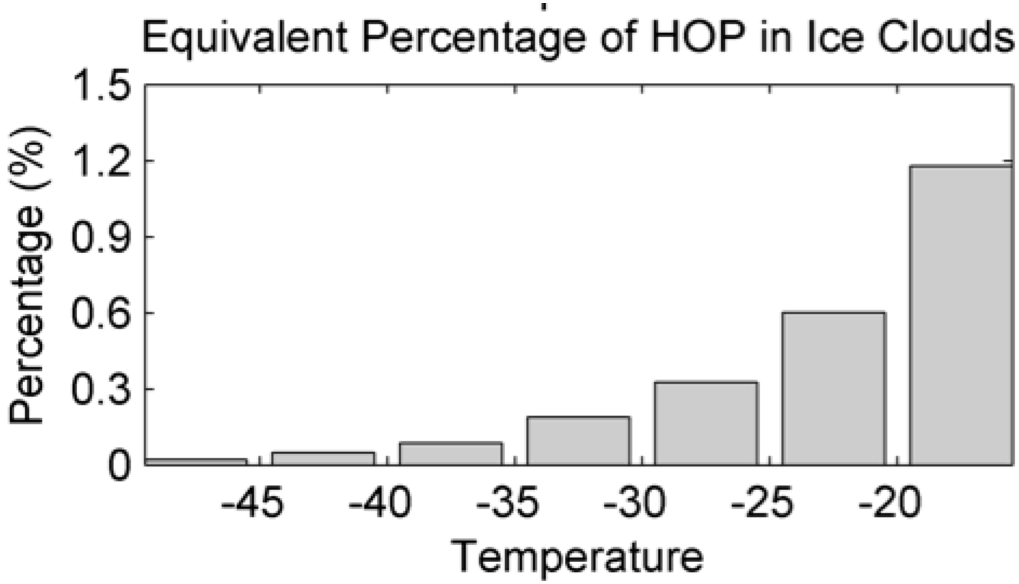
Backscatter and Depolarization Ratio Associated with Quasi-horizontally Oriented Plates within Ice Clouds (Zhou, Yang, and coauthors, 2012)





Original idea: Y. Hu et al. *Optics Express* 15, 5327-5332.





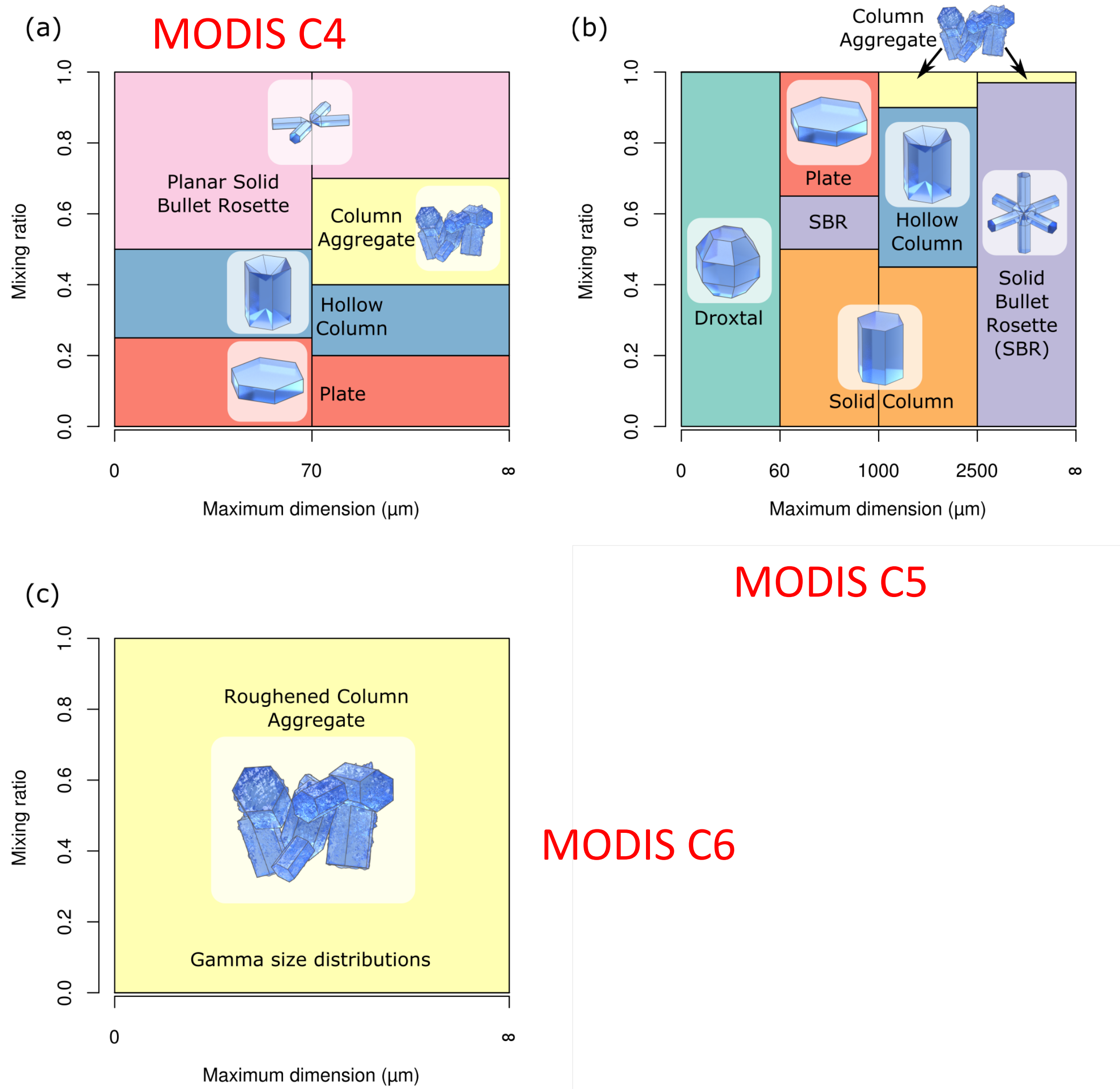
Horizontally oriented ice crystals (HOIC) exists in 46-65% optically thick clouds that are identified as ice clouds or mixed-phase by CALIPSO.

The percentage of horizontally oriented planar ice crystals (HOP) in ice clouds is quite low.

(Zhou, Yang, and coauthors, 2012)

For passive remote sensing applications, it is a valid assumption that ice crystals in the atmosphere are randomly oriented!

Ice Cloud Models used for MODIS operational ice cloud property retrievals



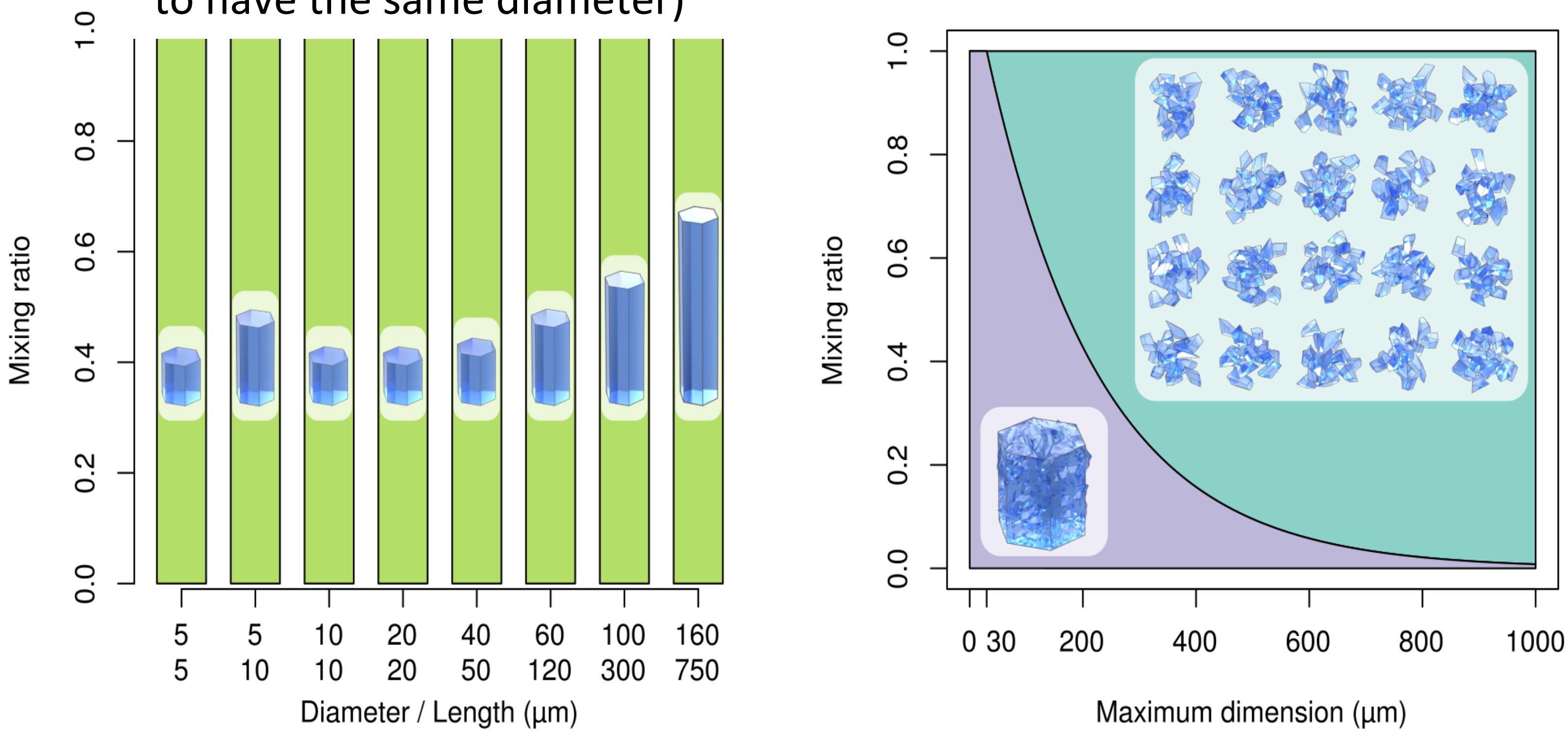
Ice particle models selected by the MODIS science team for (a) MODIS Collection 4 (King et al. 2004), (b) MODIS Collection 5 (Baum et al. 2005), and (c) MODIS Collection 6 (Platnick et al 2017).

CERES Ice Cloud Models

CERES Editions 2-4

(a) (Ice crystal images are scaled to have the same diameter)

(b) Potential CERES Edition 5

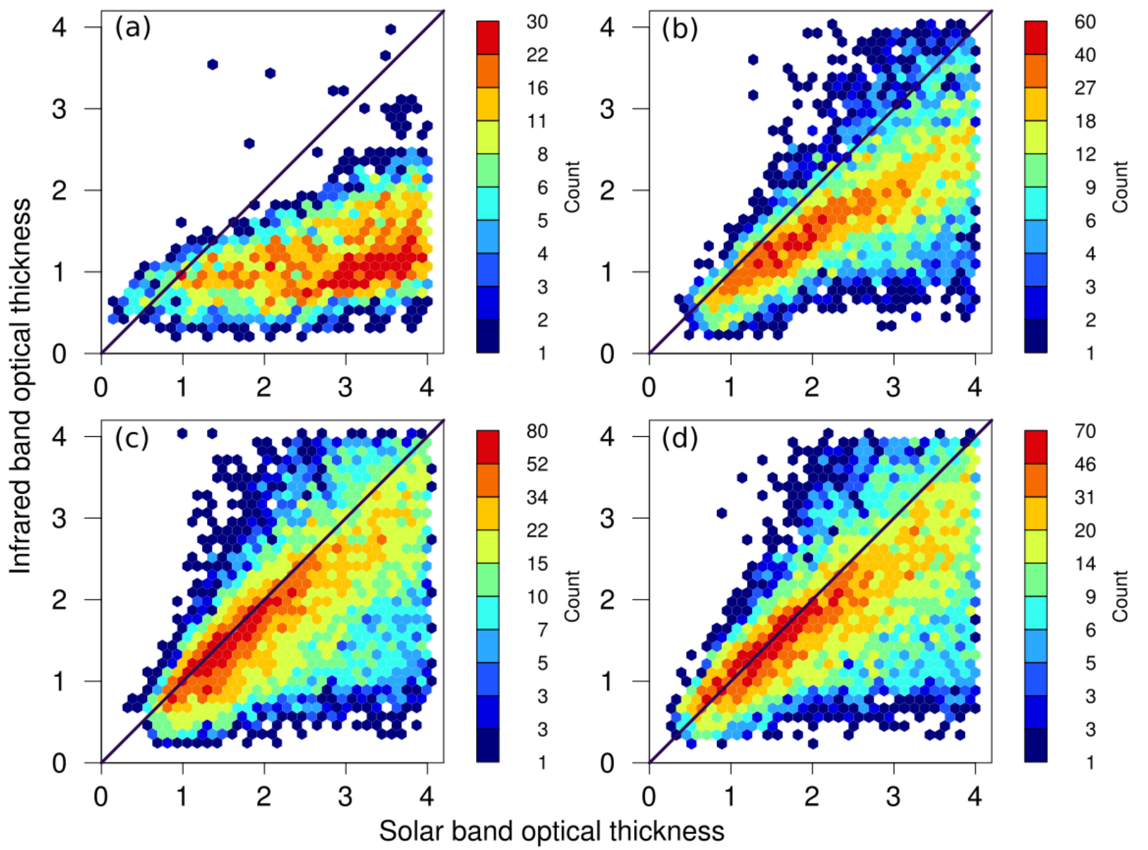


Ice particle models selected by the CERES science team: (a) a discrete model used for CERES Editions 2-4; and (b) continuous mixing ratio of two habits (potential CERES Edition 5). CERES Edition 4 model differs from Editions 2 and 3 in that <u>the particle surface is assumed to be rough in Edition 4.</u>

Consistency Check (VIS-NIR vs IR retrieval techniques)

Sphere

CERES Ed 4

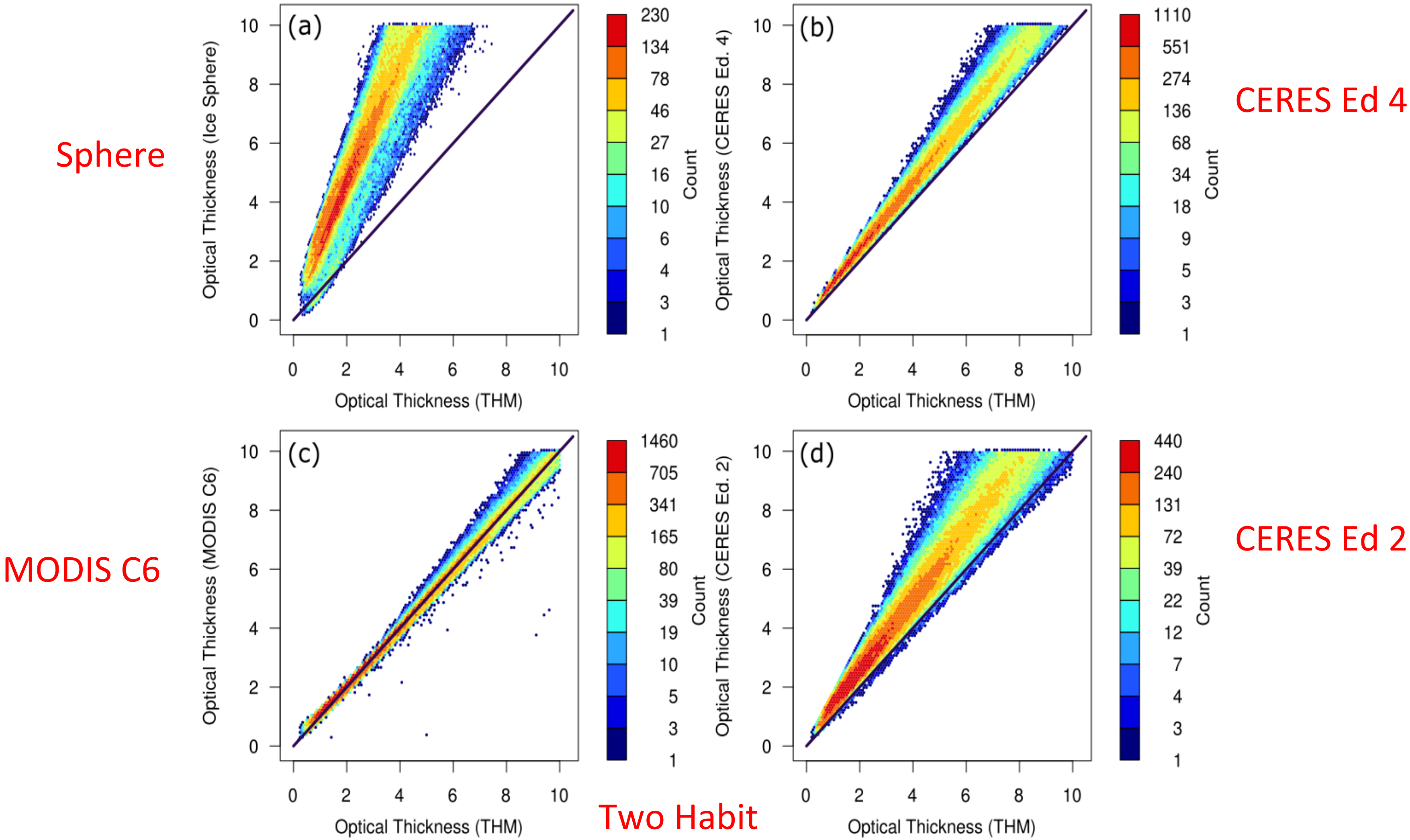


MODIS C6

Two-Habit Model

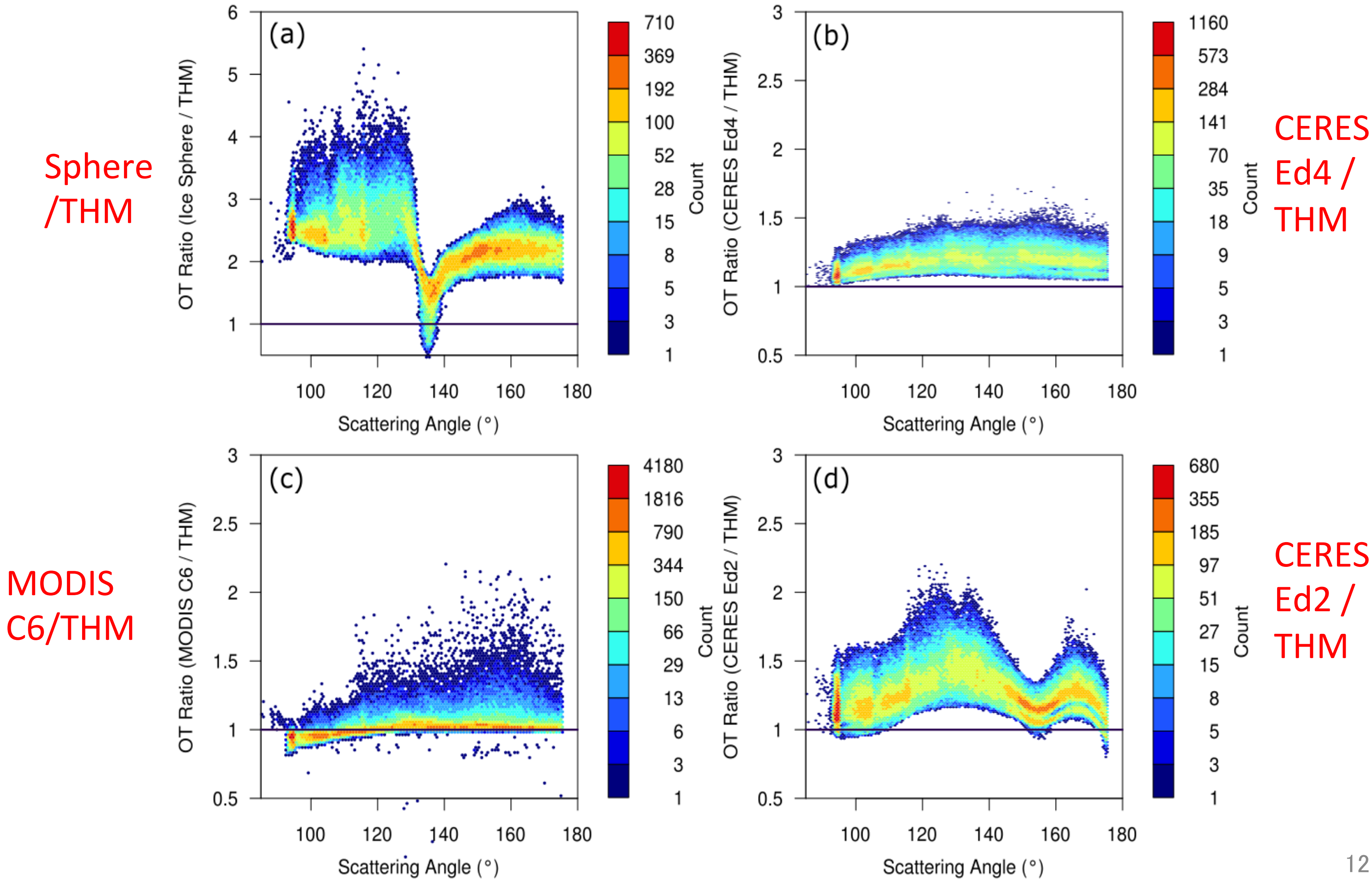
Comparison of retrieved optical thickness values from a shortwave method (the Nakajima-King bi-spectral method) and a longwave method (the split-window technique). (a) Ice sphere, (b) CERES Edition 4 model, (c) MODIS Collection 6 model, and (d) Two-habit model (Potential CERES Edition 5 model).

Comparison of retrieved optical thickness values from the shortwave technique (the Nakajima-King bi-spectral method)



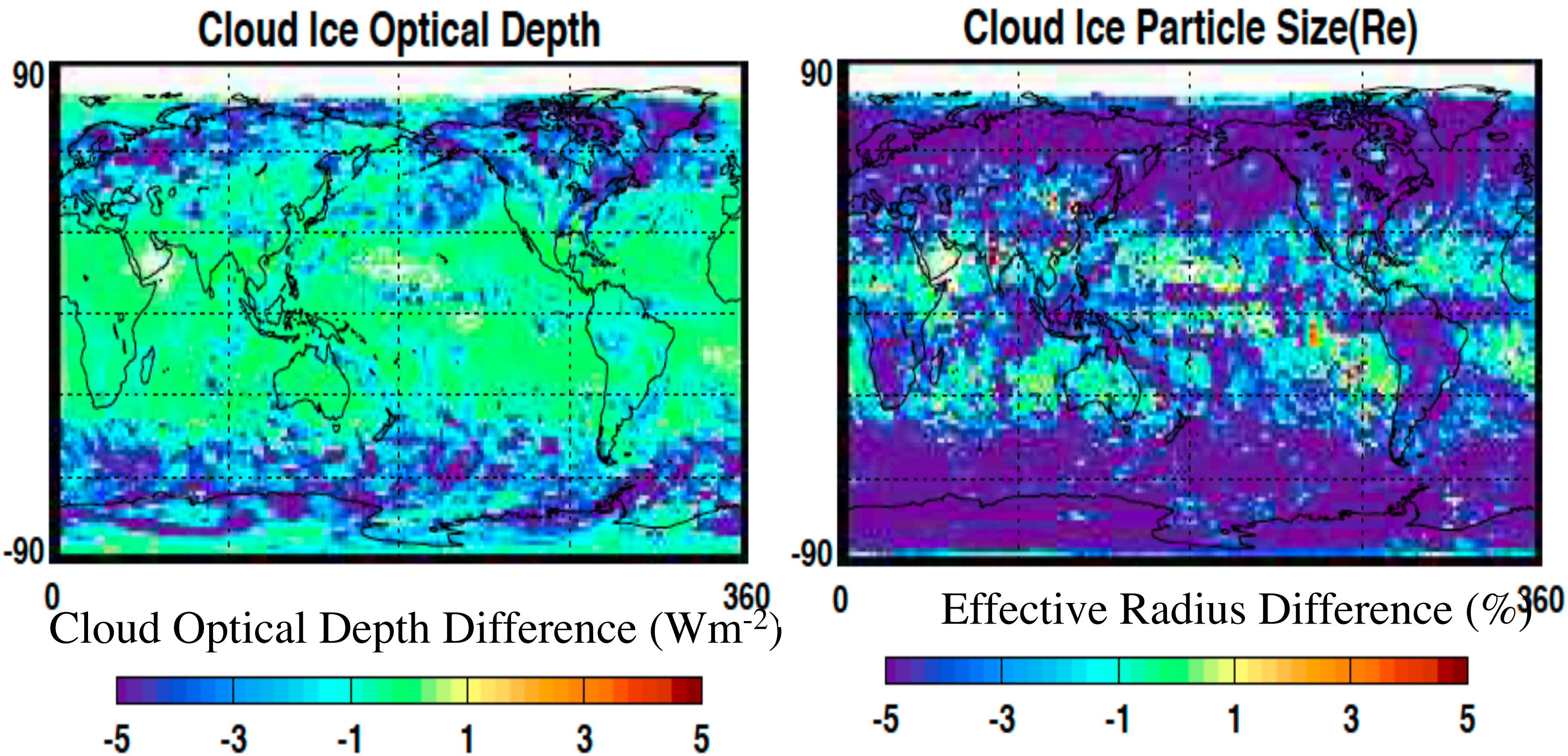
(a) Ice sphere and Two-habit model (CERES Edition 5 model), (b) CERES Edition 4 model and Two-habit model, (c) MODIS Collection 6 model and Two-habit model, and (d) CERES Edition2 model and Two-habit model.

Ratio of retrieved optical thickness values based on an ice model to the counterpart based on the Two-habit model



Loeb et al., 2018: Impact of ice microphysics on satellite cloud retrievals and broadband flux radiative transfer model calculations. *J. Climate*, 31, 1851-1864.

Cloud Property Differences at Aqua Overpass Time
(THM minus Smooth)

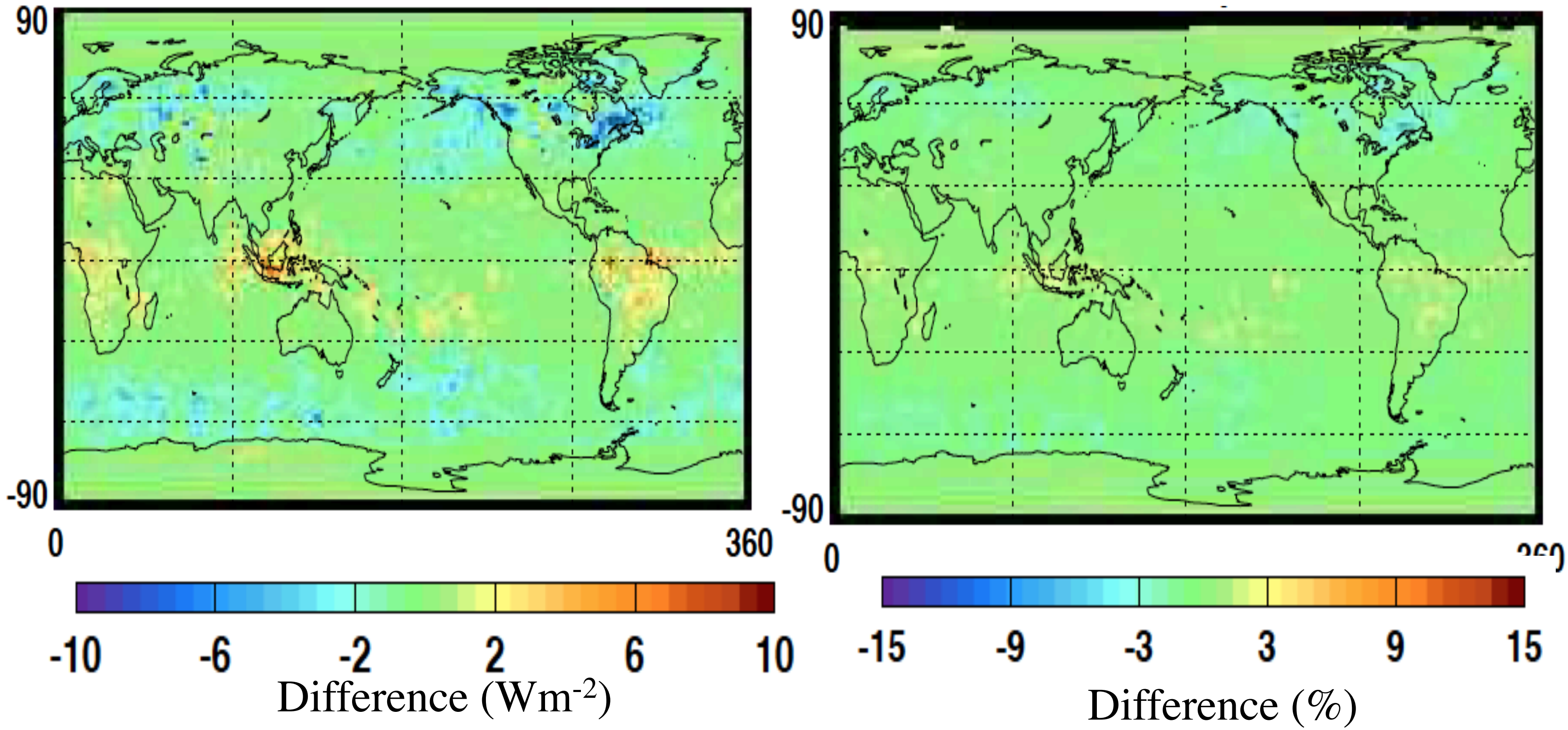


- Overall optical depth difference is -2.3 (-28% of Global Mean) and RMS difference is 2.8 (32% of GM).
- Overall effective radius difference is -3.9 ∝m (16% of GM) and RMS difference is 5.2 ∝m (16% of GM).

Loeb et al., 2018: Impact of ice microphysics on satellite cloud retrievals and broadband flux radiative transfer model calculations. *J. Climate*, 31, 1851-1864.

SW TOA Flux Difference at Aqua Overpass Time

(THM(Retriveal)/THM(Downstream) minus Smooth(Retrieval)/Smooth(Downstream))



- Overall regional RMS difference is ~1%. However, in some locations regional differences reach 3%.
- Differences tend to be positive in tropics and negative in midlatitudes.

- Findings by Loeb et al. (2018): radiative fluxes derived using a consistent ice particle model assumption throughout provide a more robust reference for climate model evaluation compared to existing ice cloud property retrievals.

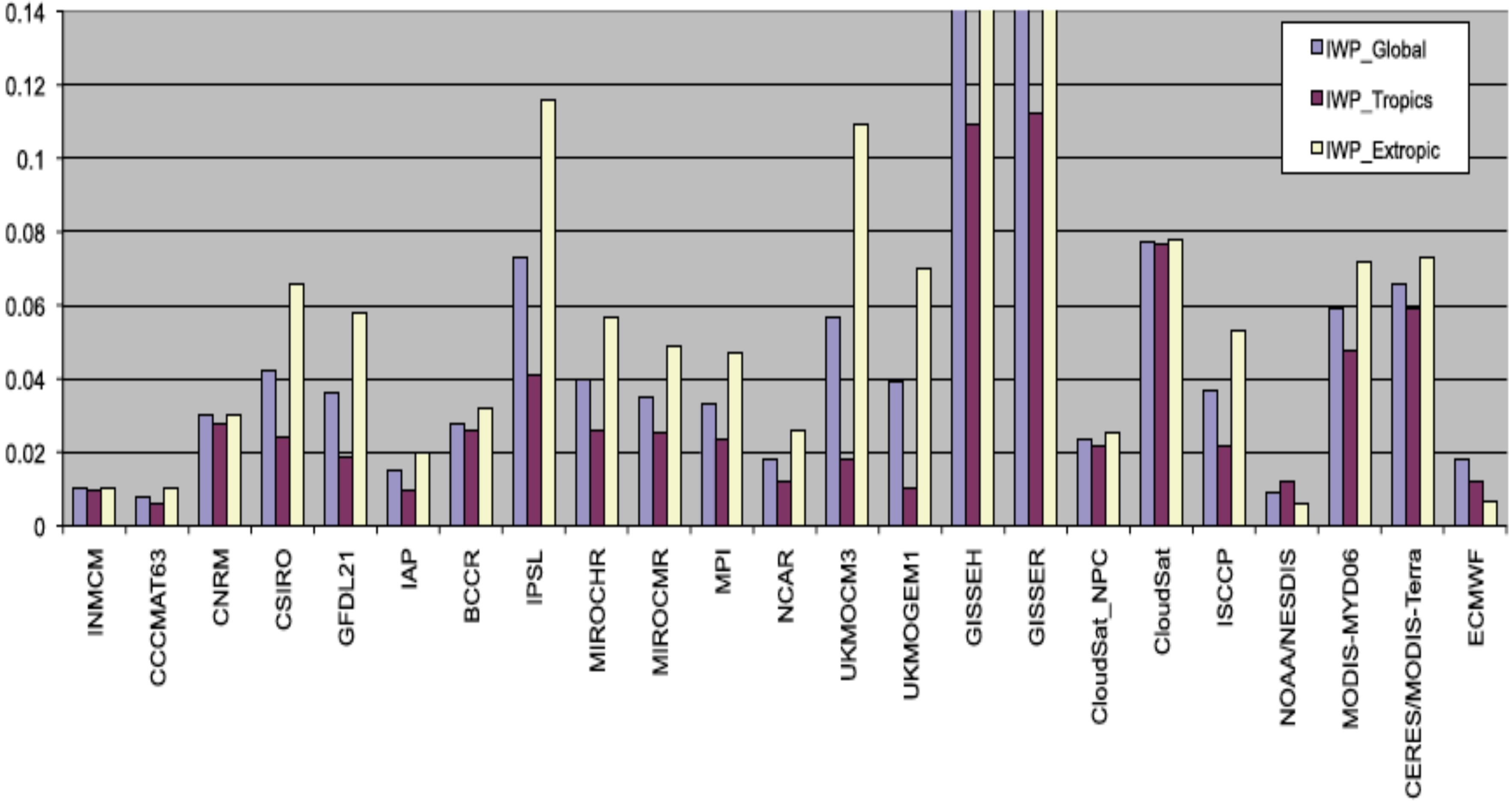
In other words, the same ice model must be consistently used in forward remote sensing implementation (look-up tables) and downstream radiative forcing assessment.

Ice Water Path (IWP),

Optical Thickness (tau)

Effective Particle size (D_{eff})

$$IWP = constant \cdot tau \cdot D_{eff}$$



Global (blue), tropical (30°N–30°S; red) and extratropical (>30°N,S; yellow) spatial mean values of cloud ice-water path (kg m^{-2}) for 23 GCM simulations (adapted from Waliser et al., 2009). Note that the blue (yellow) bars of GISSEH and GISSER that extend above the top of the plot have values of 0.21 and 0.22 (0.34 and 0.36), respectively. Observations are shown in the CERESMODIS-Terra column.

Highlight of Part I

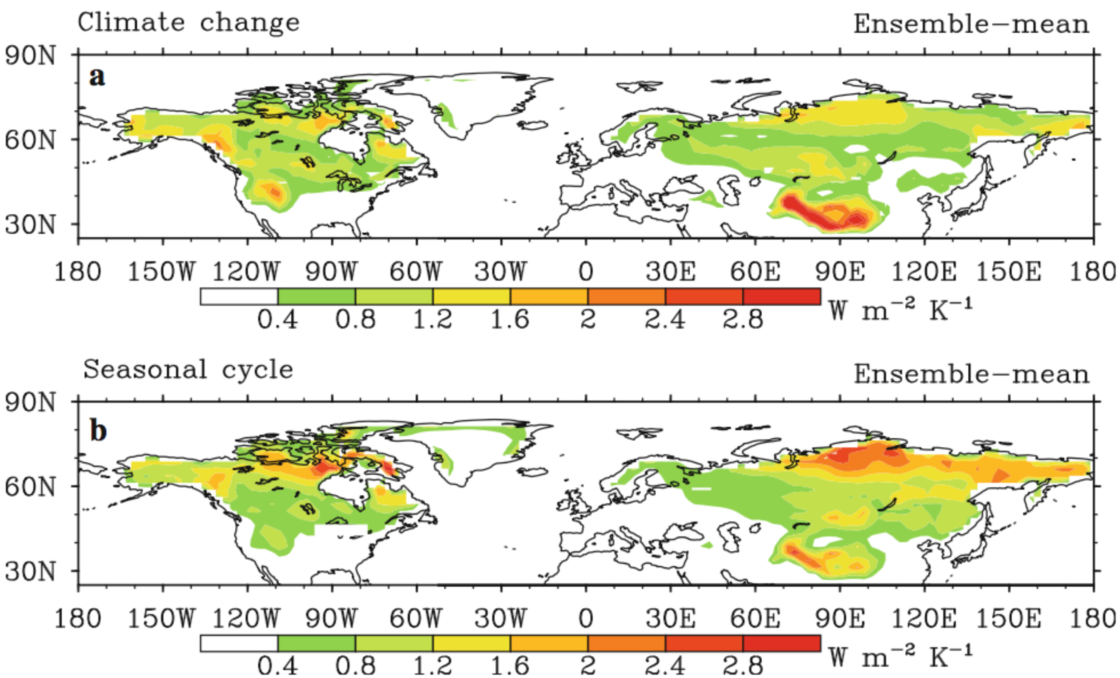
Still, it is necessary to use an optimal ice model to reliably retrieve:

- optical thickness (tau)
- effective particle size (D_{eff})

Again, IWP = constant • tau • D_{eff}

Part II—Snow Albedo Model

Snow albedo plays a dominant role in surface radiation budget in Northern Hemisphere



- Snow albedo depends on:
  1. Black carbon (BC) mixture
  2. Snow grain size
  3. Snow grain shape
  4. Multiple snow layers
- GCMs should properly take into account these snow properties in radiative transfer calculations.

Qu and Hall, 2014 ClimDyn: Snow albedo feedback is determined by (1) snow-cover shrink and (2) snow-albedo variability

Numerous snow albedo models and parameterizations have been developed based on a single-layer assumption.

but...

- Realistic snow has multiple layers.
- It is sufficient to assume two-layer snow to reproduce observed snow albedo with radiative transfer calculations (Grenfell, 1994)

Objectives

- Investigate the sensitivity of snow albedo to snow microphysical properties based on a two-layer snow model.

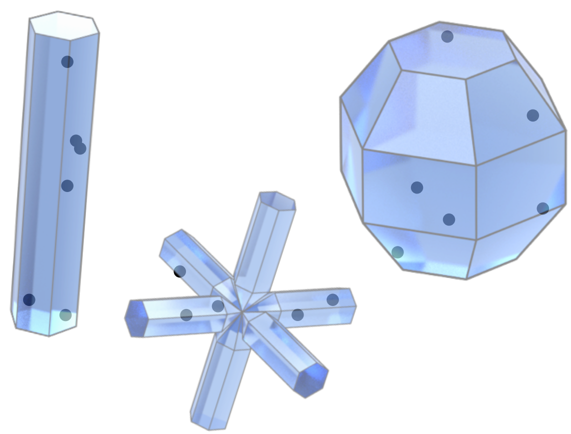
- Develop a two-layer snow surface albedo parameterization scheme for NASA Langley’s modified Fu-Liou broadband radiative transfer model.

Expected significance:

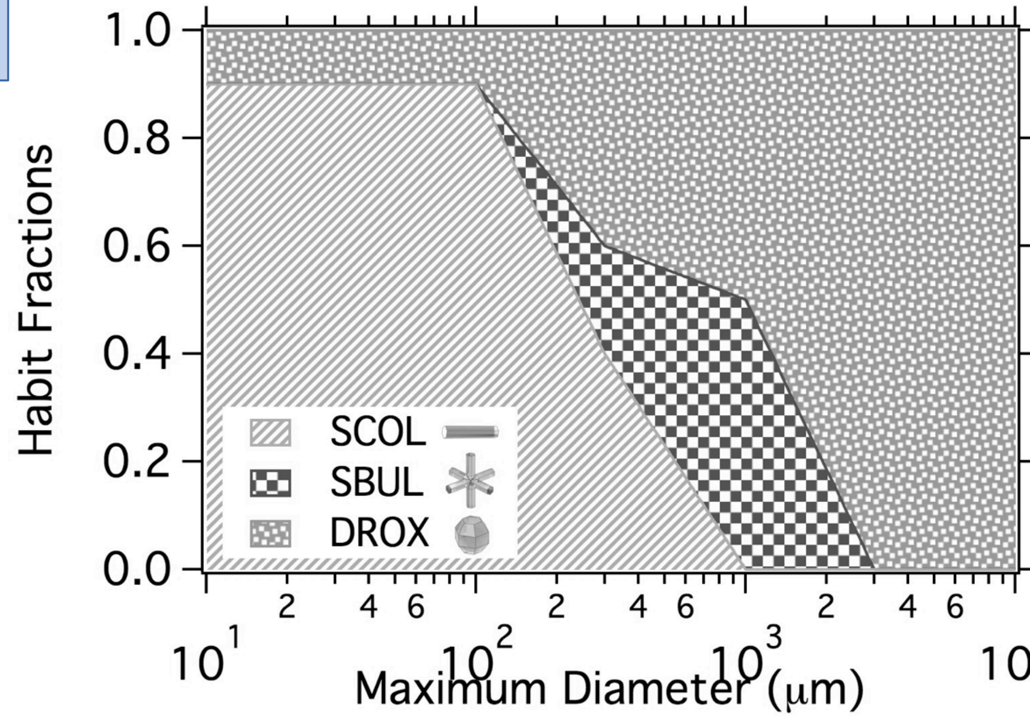
Reduce uncertainty in estimating the surface radiation budget associated with snow albedo.

Bulk Snow Optical Property

Snow Grain Habit Mixture



Details are presented in the previous CERES meeting



- Snow Grain Habit Mixture (SGHM) model (CERES meeting in May 2018).
- BC internal inclusions in snow particles are considered.
- Particle size distribution (PSD) is parameterized in terms of the gamma distribution based on in situ measurements.

Two-layer Snow Albedo Model

Input

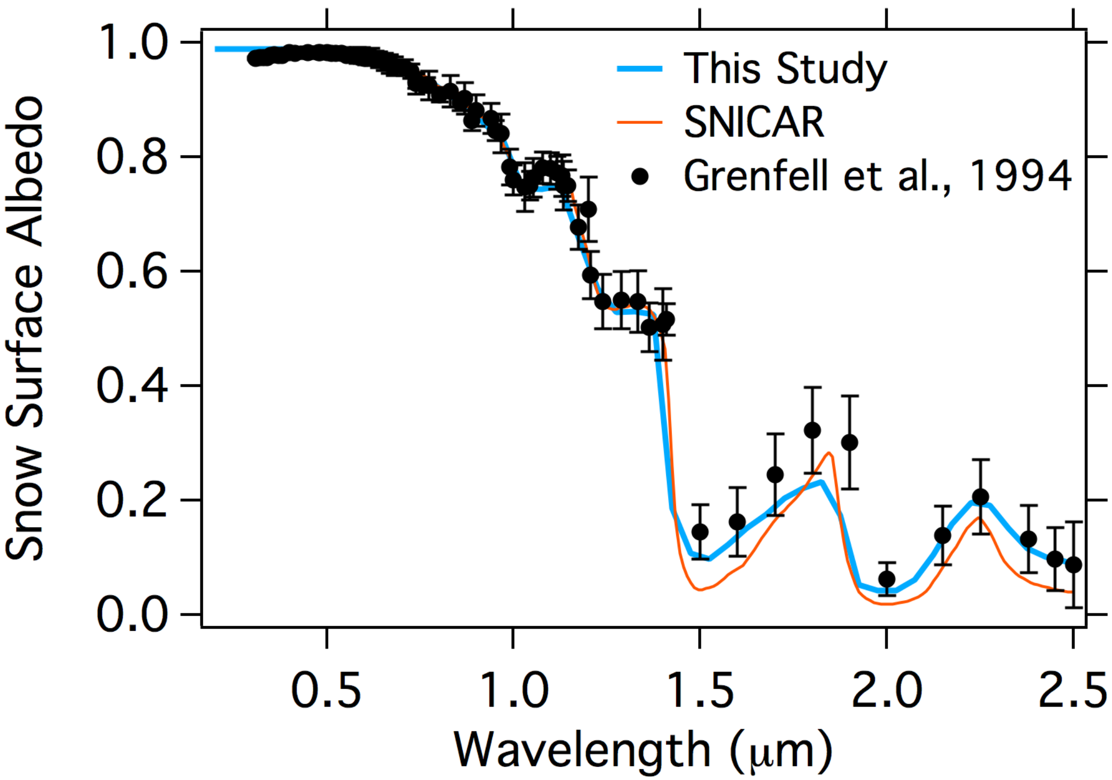
Top layer: SWE_1, R_{e1}, C_{BC}
Second layer: R_{e2}, C_{BC}

Assumption

- C_{BC} is constant over layers
- SWE_2 corresponds to optical thickness = 960

- Snow albedo simulations:
  - Vector adding-doubling RTM (Huang et al., 2015)
  - Plane parallel homogeneous snow layers
  - Optically semi-infinite depth of second snow layer
  - Snow grain habit mixture (SGHM) model Variables:
  - Top layer Snow Water Equivalent (SWE_1)
  - Effective radii (R_{e1}, R_{e2})
  - BC internal mixing (C_{BC})

Comparison



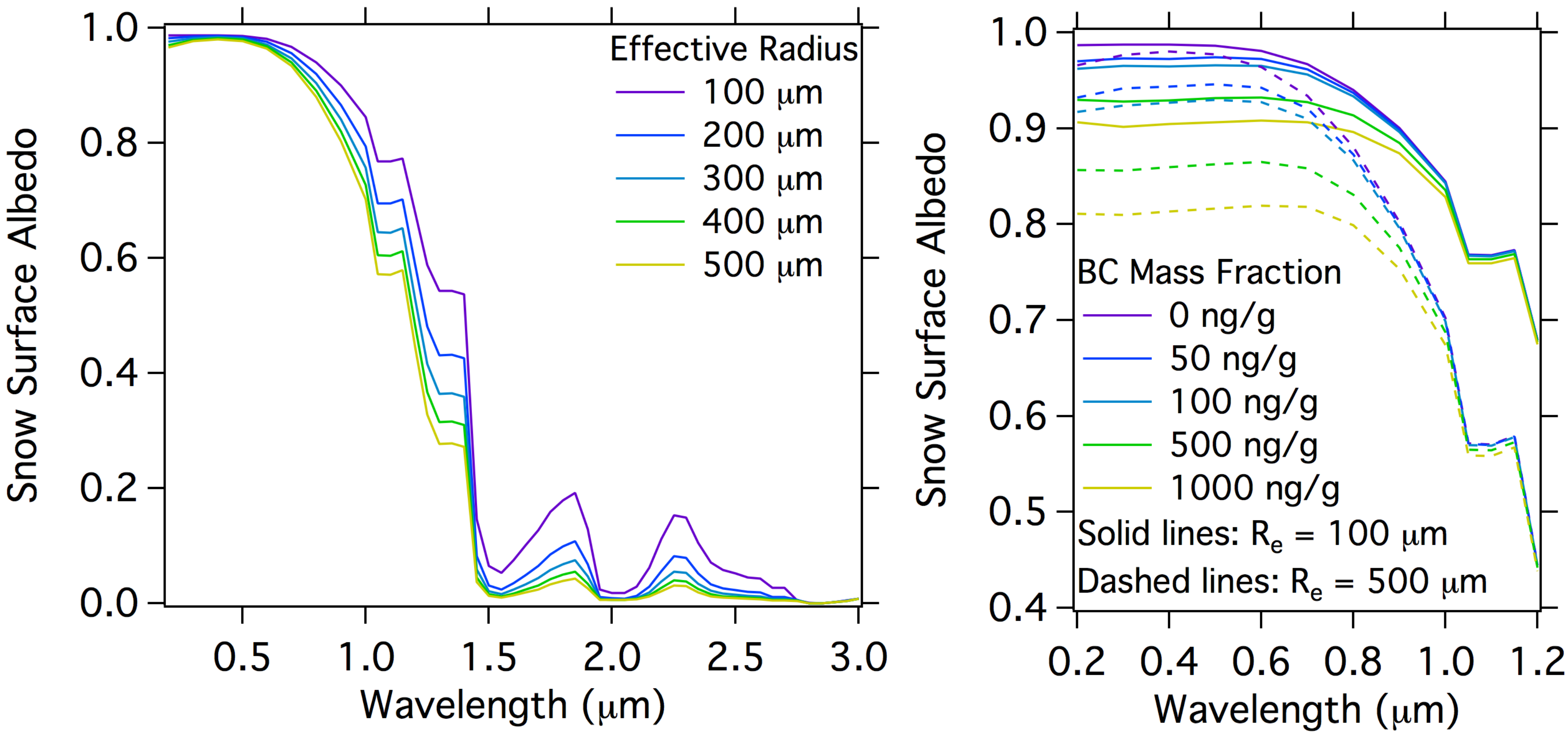
SNICAR model: (Flanner et al., 2007)
- Single-layer
- Effective radius = 80 ∝m (taken from Yasunari et al., 2012)

This study:
- Two-layer
- Effective radius = 52 μm (top), 160 μm (second)

- Two-layer snow albedo model reproduce the observed snow albedo in Antarctica (Grenfell et al., 1994).
- Our model is comparable to SNICAR model in the visible to 1.5 ∝m region and outperforms in the 2.0–2.5 ∝m region.

Sensitivity Study (1/4)

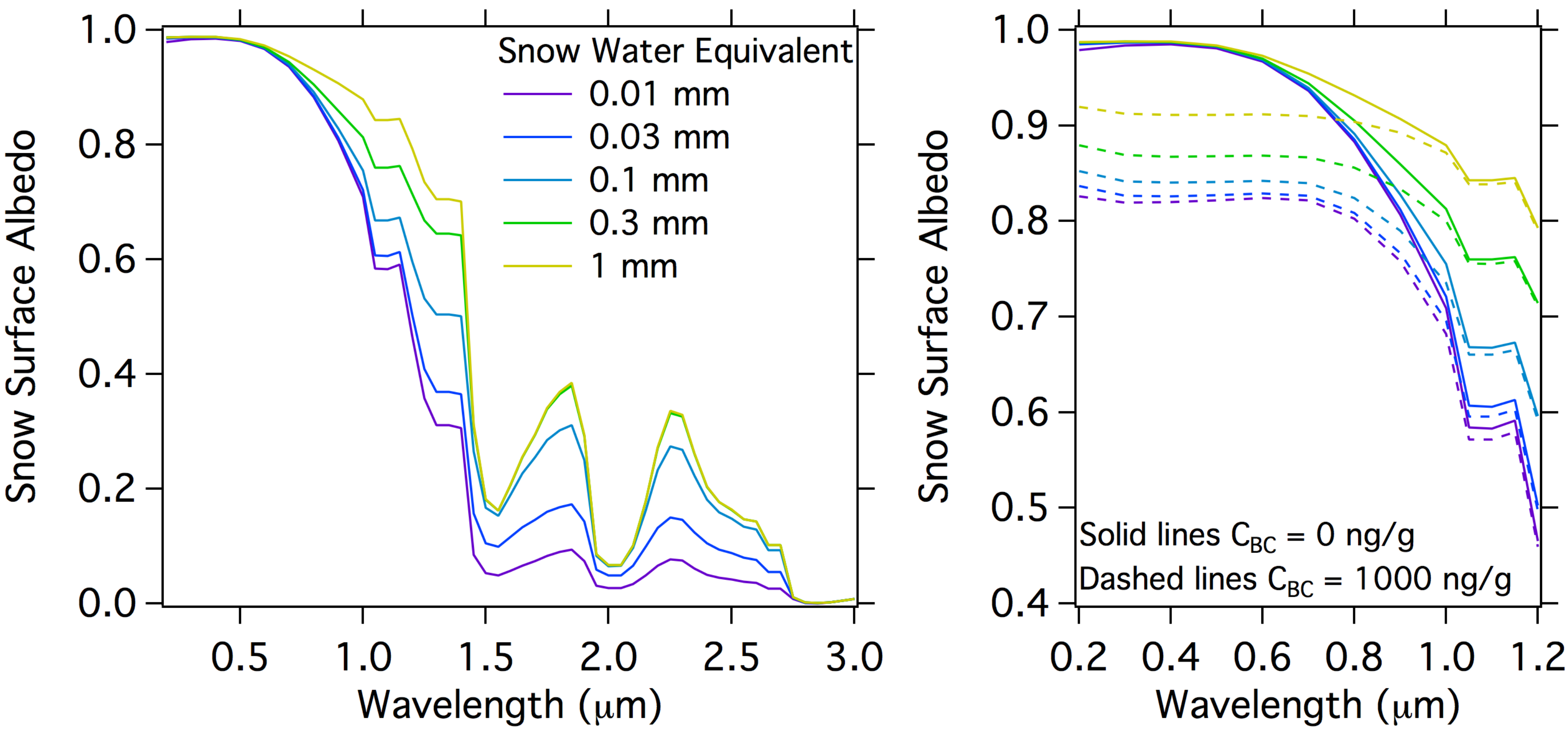
Single layer snow



- Snow albedo is sensitive to the effective radius at near-infrared wavelengths and to BC internal mixing at visible wavelengths, as noticed by many previous studies.

Sensitivity Study (2/4)

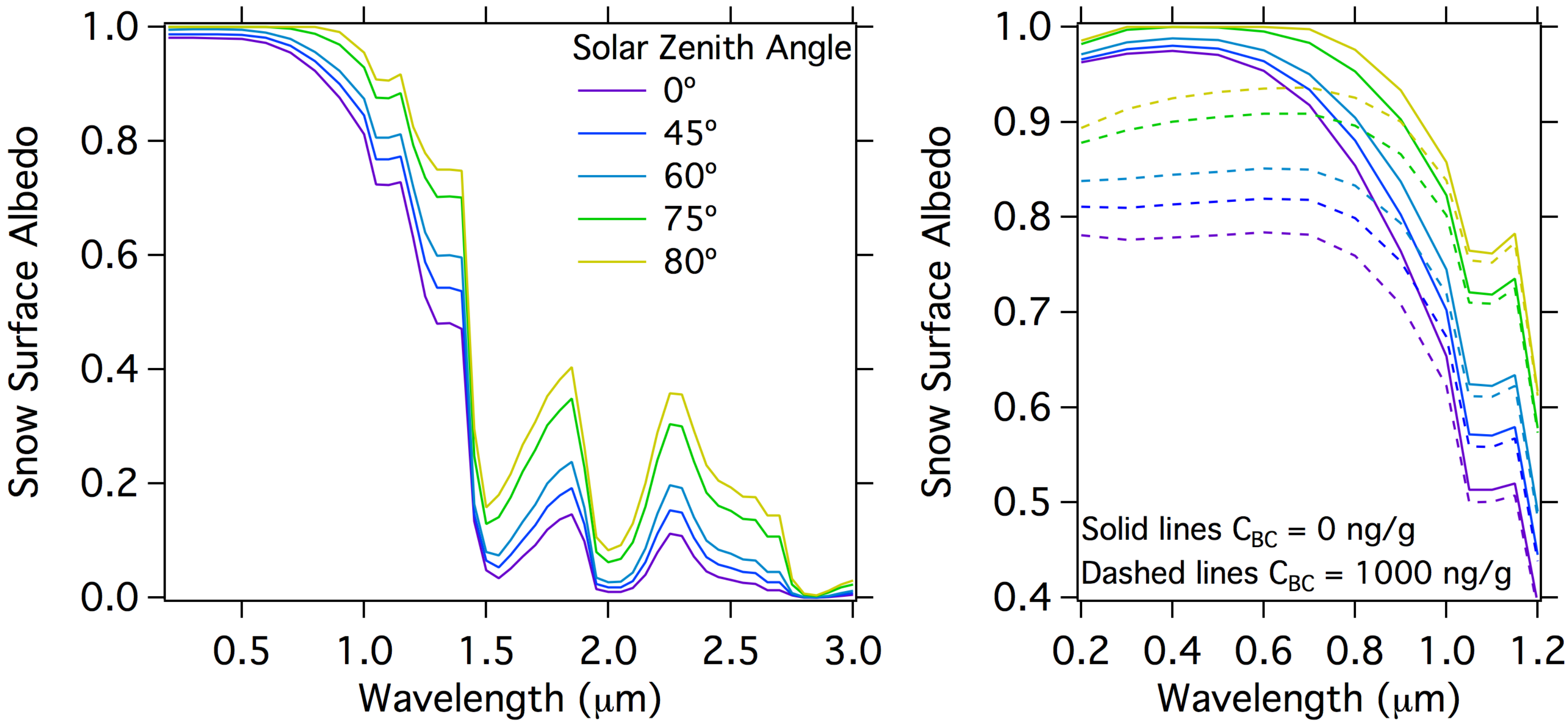
Two-layer snow $R_{eff1} = 30\ \mu m$, $R_{eff2} = 500\ \mu m$



- SWE in the top layer significantly changes snow albedo at near-infrared wavelengths even if SWE is small.
- SWE effects visible snow albedo for polluted snow layers.

Sensitivity Study (3/4)

Single layer snow

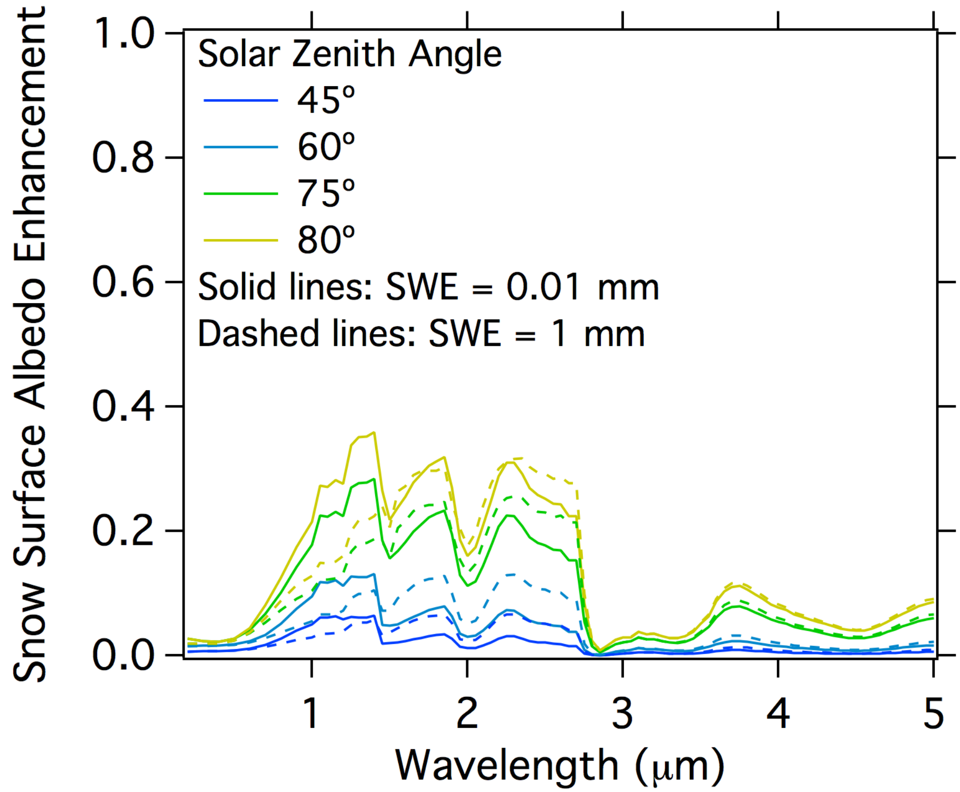


- Snow albedo is enhanced at high SZAs.
- The sensitivity is similar to that associated with the effective radius at near infrared wavelengths, but not at visible wavelengths
- SZA dependence of snow albedo is enhanced for polluted snow.

Sensitivity Study (4/4)

Two-layer snow

$$R_{\mathrm{eff1}} = 30 \propto \mathrm{m},\ R_{\mathrm{eff2}} = 500 \propto \mathrm{m}$$



- The top layer snow properties play a major role in the SZA dependence of snow albedo, especially in the near-infrared regime.

Snow Albedo Parameterization (1/4)

Based on the sensitivity of snow albedo to these snow characteristics, we developed snow albedo parameterizations:

- ✓Single layer snow albedo parameterization (not discussed in this presentation)
- ✓Two-layer snow albedo parameterization

Snow Albedo Parameterization (2/4)

Two-layer snow

$s_{t,i}$, and t_0 are coefficients for two-layer parameterization determined through the regression. Subscript t = two-layer

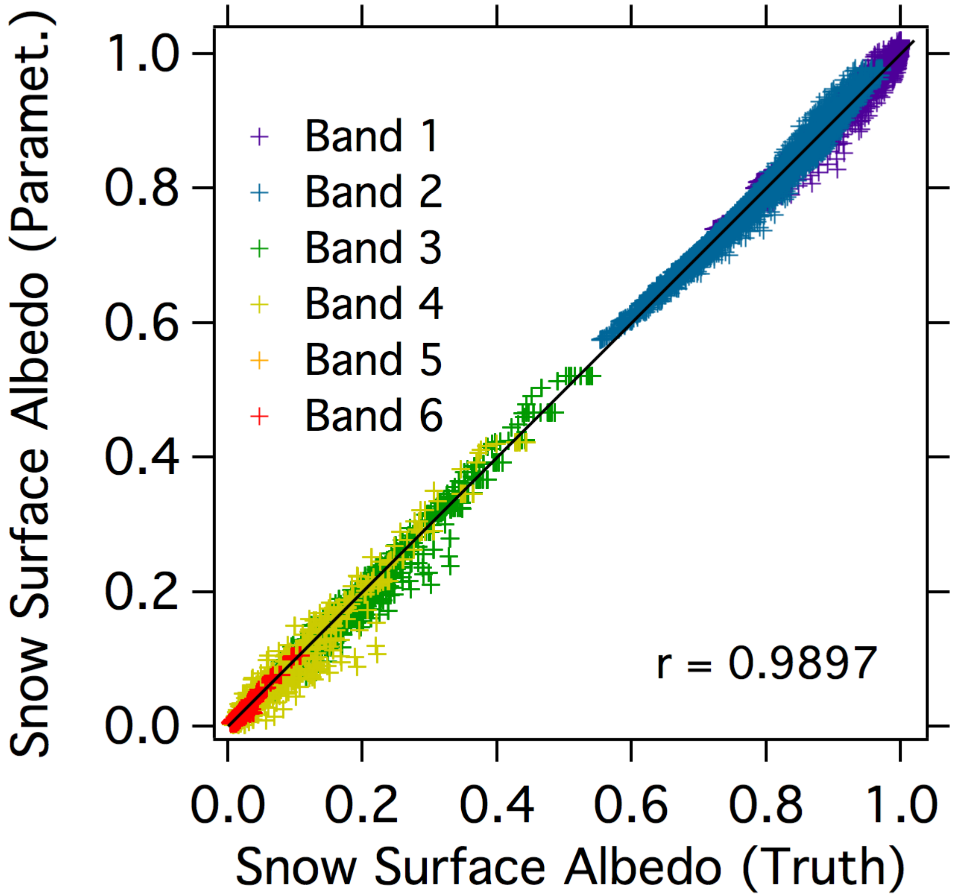
$$R_n = \left(1 - e^{-t_0 \frac{w}{R_{e1}\mu_0}}\right)\left(\frac{R_{e1}}{R_0}\right) + e^{-t_0 \frac{w}{R_{e1}\mu_0}}\left(\frac{R_{e2}}{R_0}\right) \quad \text{where } R_o = 30\ \mu\text{m} \qquad (1)$$

$$\alpha_{t,enh} = l_n \left(\frac{1-\mu_0}{1+\mu_0}\right)^{s_{t,0}} \quad \text{where} \quad l_n = s_{t,1} + s_{t,2}\,\alpha_{s,0}^{\ s_{t,3}} \qquad (2)$$

$$\alpha_t = \alpha_{t,0} + \alpha_{t,ehn}(\alpha_{s,0}) \quad \text{where} \quad \alpha_{t,0} = \alpha_{t,pure} - \Delta\alpha_t \qquad (3)$$

- For two-layer snow albedo parameterization, we use a formula for representative snow albedo ($\alpha_{t,0}$) similar to He et al., (2018b), but we use R_n given by Eq. (1).
- Snow albedo enhancement is calculated based on $\alpha_{s,0}$ from **single layer parameterization** (with the top layer snow properties)
- Derive snow albedo based on two-layer snow by Eq. (3)

Snow Albedo Parameterization (3/4)

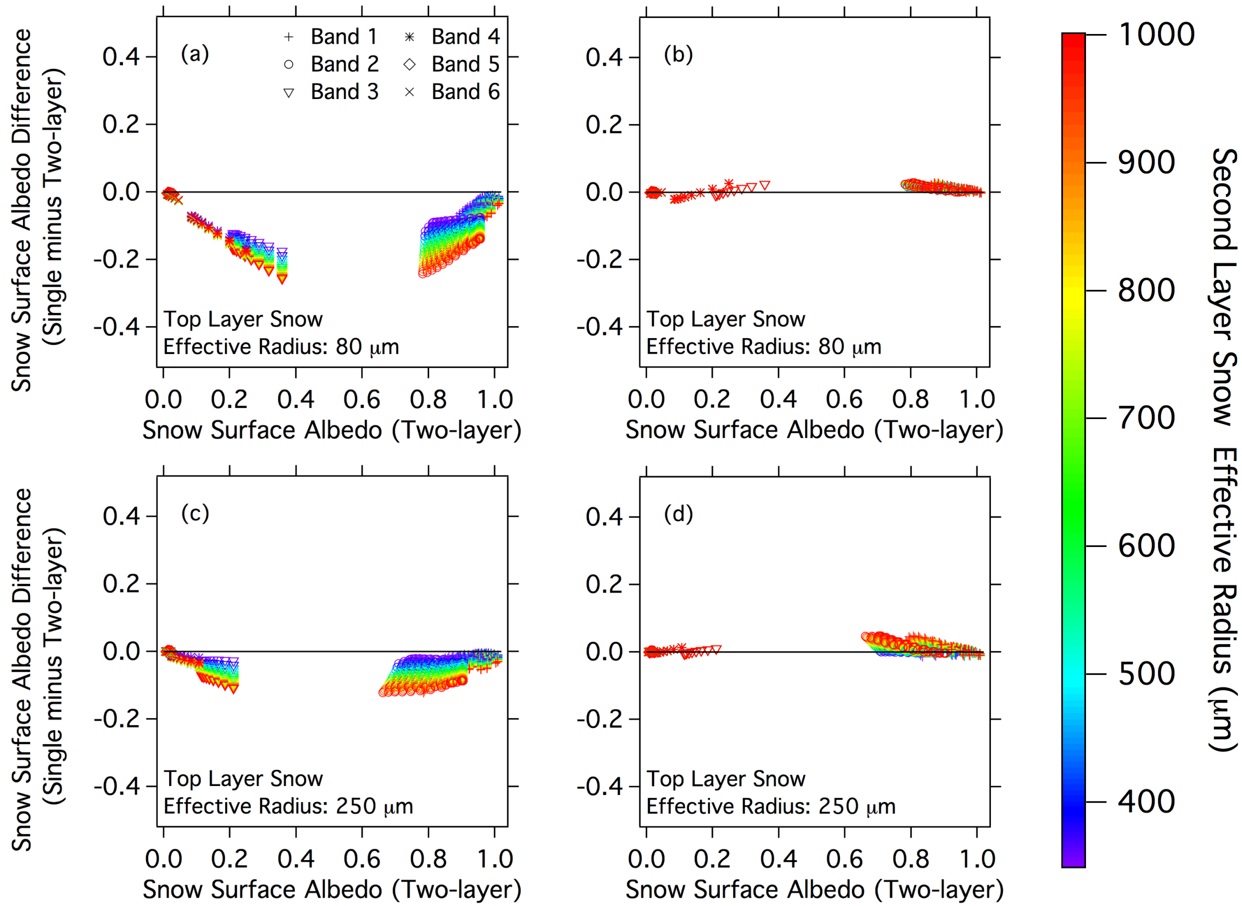


- Band snow albedo values simulated with a rigorous radiative transfer model and the parameterization scheme for the bands of NASA Langley's modified Fu-Liou model.
- The correlation coefficient is close to 0.99.

Snow Albedo Parameterization (4/4)

Ignore the top layer

Ignore the second layer



- If we ignore the first layer snow with 2-cm thickness, snow albedo is underestimated by up to 0.3, depending on snow microphysical properties.
- Ignoring the second layer snow leads to a slight increase in snow albedo.

Summary of Part II

- We investigated the sensitivity of snow albedo to snow microphysical properties based on a two-layer snow model.

- We developed single- and two-layer snow albedo parameterizations for NASA Langley's modified Fu-Liou radiative transfer model.

- Future work: extend the snow albedo model to a snow BRDF or PBRDF model for remote sensing applications.